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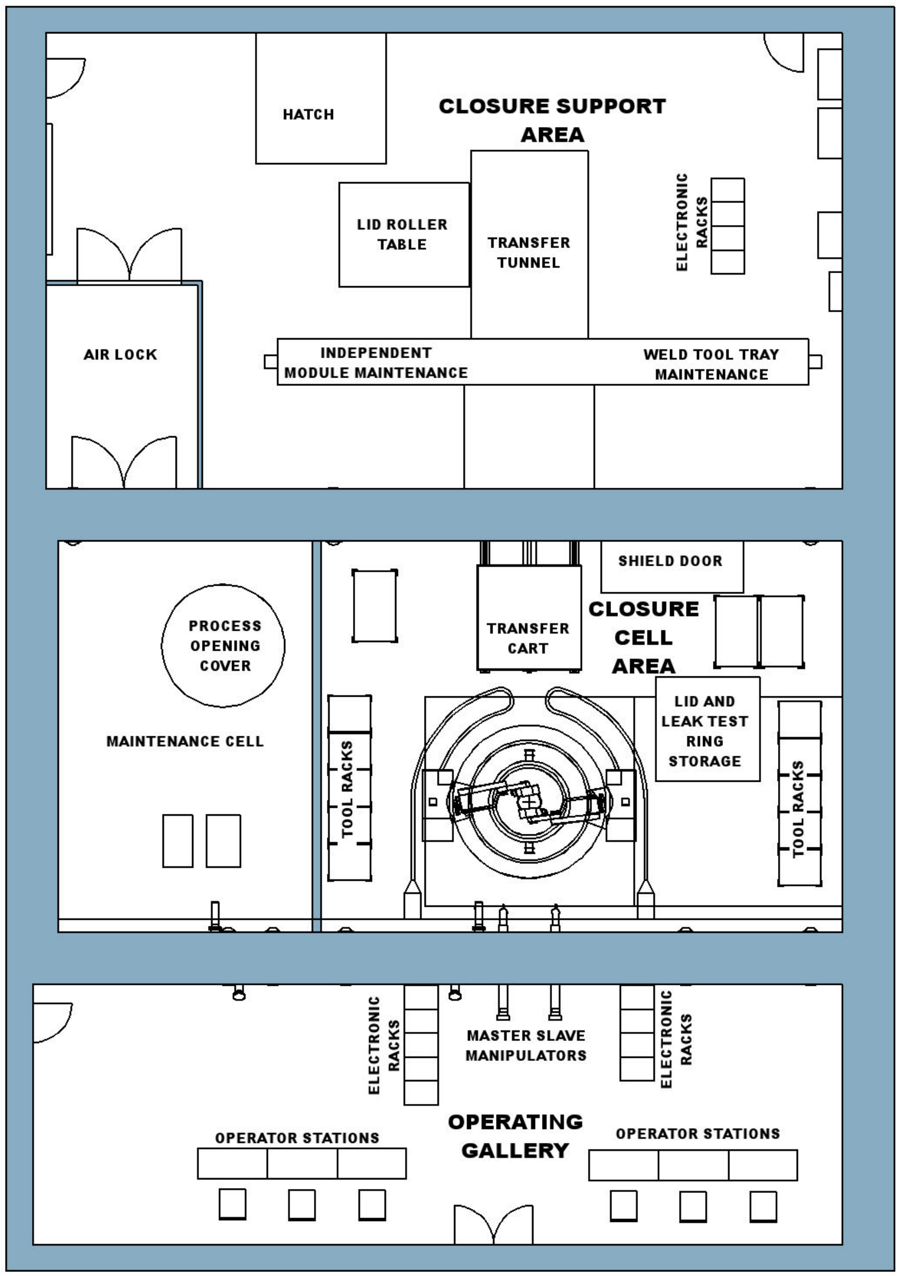
Nuclear reactors for generating energy and conducting research have been in operation for more than 50 years, and spent nuclear fuel and associated high-level waste have accumulated in temporary storage. Preparing this spent fuel and nuclear waste for safe and permanent storage in a geological repository involves developing a robotic packaging system—a system that can accommodate waste packages of various sizes and high levels of nuclear radiation.

During repository operation, commercial and government-owned spent nuclear fuel and high-level waste will be loaded into casks and shipped to the repository, where these materials will be transferred from the casks into a waste package, sealed, and placed into an underground facility. The waste packages range from 12 to 20 feet in height and four and a half to seven feet in diameter. Closure operations include sealing the waste package and all its associated functions, such as welding lids onto the container, filling the inner container with an inert gas, performing nondestructive examinations on welds, and conducting stress mitigation.

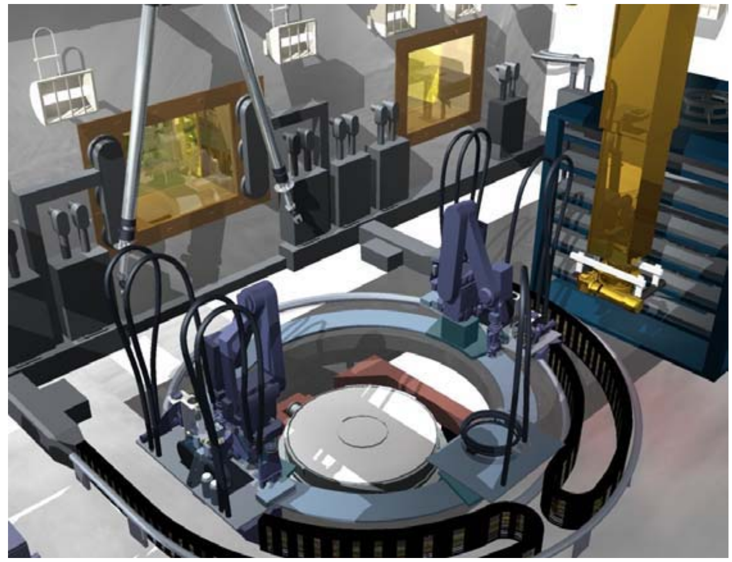
The Idaho National Laboratory is designing and constructing a prototype Waste Package Closure System (WPCS). Control of the automated material handling is an important part of the overall design. Waste package lids, welding equipment, and other tools must be moved in and around the closure cell during the closure process. These objects are typically moved from tool racks to a specific position on the waste package to perform a specific function. Periodically, these objects are moved from a tool rack or the waste package to the adjacent glovebox for repair or maintenance. Locating and attaching to these objects with the remote handling system, a gantry robot, in a loosely fixtured environment is necessary for the operation of the closure cell. Reliably directing the remote handling system to pick and place the closure cell equipment within the cell is the major challenge.



The Challenge

The challenge associated with equipment transfer is to know the location of tools and equipment after they are placed on the transfer cart and rolled either into or out of the closure cell and, equally as challenging, to place or position tools and equipment on or above a waste package that has a loose positioning tolerance.

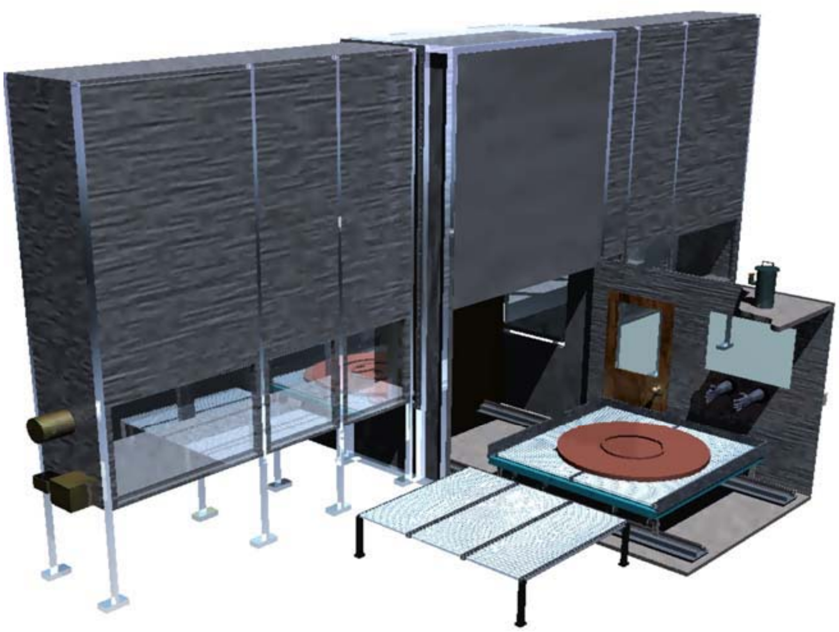
The layout plan of the waste package closure system is shown to the right. An opening in the cell floor allows access to a waste package by two welding robots and closure tools, which are mounted on a circular bearing platform. Three types of connecting mechanisms are incorporated into different tools and equipment that require automated coupling/decoupling in the waste package closure cell (see the figure to the right): a lid lifting ring, a quick change tool plate, and a tool tray tool plate.



The closure process is estimated to take about 44 hours. That means that about every two days the robotic material handling system must couple and decouple at least two welding and inspection system tool trays (these contain welding and inspection end-effectors, weld wire, repair end-effectors, etc.) from the bearing platform and transfer them to the maintenance glovebox. A quick-change tool plate mounted to the top of the tool tray allows coupling to the handling system. A custom tool plate on the bottom of the tool tray allows power and control to be coupled to the tool tray when it is placed on the bearing platform. Two spare tool trays must be moved from their fixtured storage locations to the bearing platform. In addition, a waste package identification end-effector (bumpy barcode reader), a debris cleanup tool, a waste package purge and inerting tool, and a weld seam leak test tool will each be deployed at least once in the closure procedure.

In an off-normal event, the handling system may have to locate the welding and inspection system tool trays at an unknown location on the circular bearing platform that surrounds the process opening (again, see the figure above). If a tool should fail in the closure cell, the remote handling system would be required to move the tool to the transfer cart (a cart that rolls between the maintenance glovebox and the closure cell) for transfer to the maintenance glovebox for repair. The tool could be located on the waste package or in a tool rack. If located on the lifting ring of one of the lids of the waste package, that position must somehow be identified. If the tool is located in a tool rack, these positions are known.

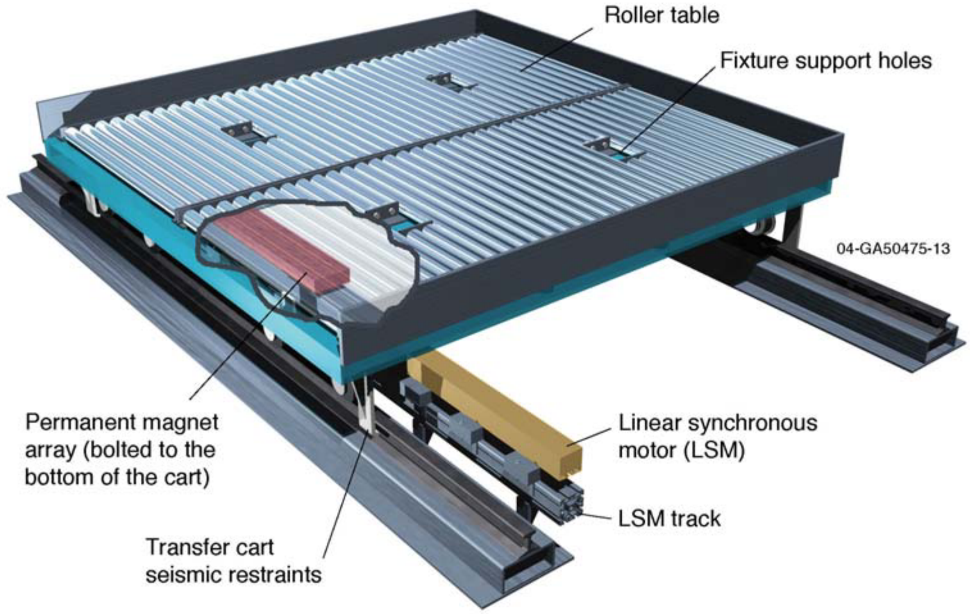
The waste package positioning specification is ±2 inches on X, Y, and Z axes and ±½ inch on level. This means that when the waste package is moved into the closure cell area, those moving the package must position it within these tolerances. This creates the requirement to accurately determine the position of the waste package in robot space. Without this information, the weld and inspection robots would not know where to position the welding end-effectors to begin a weld.



The identification marks and index on the waste package and lids must also be accurately known. These marks help to associate the correct waste package lids with the waste package and to establish a point of reference on the waste package for all weld and inspection information collected during the closure process.

Transferring the tools and equipment from the closure cell to the maintenance glovebox is another challenge. A linear-motor-driven cart moves through a radiation shield door from the closure cell to the maintenance glovebox, conveying waste package lids into the closure cell and tools back and forth between the glovebox and the closure cell. The figure to the left is a cut-away view of the glovebox lid load-in area, showing a lid sitting on the transfer cart ready to be transferred to the closure cell.

Fixturing of all of the various tools and waste package lids on the transfer cart will be difficult and will require very accurate positioning of the cart. The cart design shown in the figure to the right incorporates rollers on the surface of the cart to accommodate loading of waste package lids onto the cart for transfer into the closure cell. It includes fixture support holes for precision mounting of fixtures for each piece of equipment being transferred and removed when lids are transferred into the cell. The transfer cart positioning must be within ±1/16th-inch repeatability to enable automatic pick and place of securely fixtured objects. The lids will also have to also be rotated to a known position on the cart to ensure the remote handling system can reliably couple to it. Rotating the lids on the cart would be difficult because of the weight of each lid (up to 1500-lb) and maintaining an accurate position while rolling a lid onto the cart from the roller table (lid staging area) will not be trivial. Fixturing the lid is complicated by the requirements that (1) the lid is considered part of the corrosion barrier of the waste package and must not come in contact with any material other than stainless steel, and (2) the weld surfaces on the lid are precisely machined and must not be damaged.



Another challenge associated with the transfer of equipment and materials between the closure cell and the maintenance glovebox is picking a tool or piece of equipment from the transfer cart and placing it on a fixture in the glovebox designed to hold it for maintenance or repair. Once again, the challenges lie in ensuring the location of the tool or piece of equipment on the transfer cart.

The Solution

Searching for a solution has led to vision guidance for the robot technologies. Initially, we investigated multicamera techniques but we finally rejected these because of complications associated with using multiple cameras in a high-radiation area. In our applications, three to four cameras would be needed at each pickup location to image the tool or equipment. This becomes unmanageable with the numbers of end-effectors, lids, and tools required in the waste package closure process.

A simpler solution was found to be a single-camera 3-D imaging (SC3D) system capable of finding the 3-D location of a tool or piece of equipment and communicating to the robot the coordinates in robot space where the object resides. We selected a radiation-hardened camera found to have adequate resolution to image a lid lifting ring, the quick change tool plate mounted to the tools and equipment, and the tool tray tool plate mounted on the bearing platform.

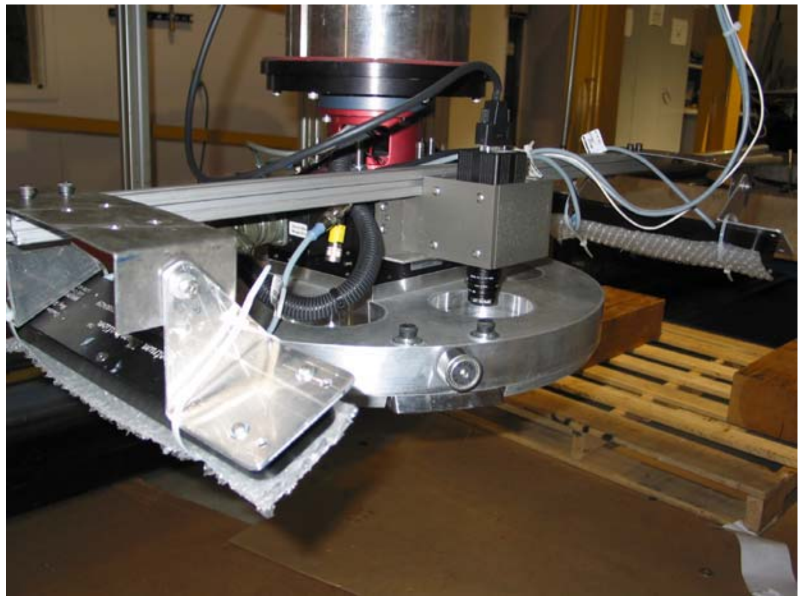
The position of the waste package in the process opening and the location of identification and index marks on the waste package and lids can be determined using the SC3D system. Unique and consistent index marks were defined for the lid lifting rings and the waste package to allow accurate positioning of the waste package to be determined. We also used these unique markings to define the location of the identification codes imprinted on the lid lifting rings for automatic deployment of the bumpy barcode reader.

When a welding and inspection tool tray located on the revolving platform near the process opening needs to be picked up, a general location needs to be defined so that the SC3D system can locate the tool plate in the camera's field of view. We are considering several techniques for this purpose, including automatic scan and operator interaction. Once the tool plate on the tool tray is within the field of view, the location of the tool tray can be accurately calculated.

We can accurately determine the position of the waste package in the process opening by locating the inner lid lifting ring. The waste package is delivered with the inner lid set in place, and the dimensions of the waste package are very accurately defined, so locating the lifting ring in robot space allows the location of the waste package to be calculated and communicated to the welding robots so that the seam to be welded can be located.

Finding a tool or tool tray that has been placed on the transfer cart remains a challenge because the closure cell gantry robot has limited axes of motion. A rack that will allow the tools to remain level will be needed, or the tool design will have to maintain a level stance when placed on a flat surface. Accurate positioning of the tool in the rack or on the cart is not necessary as long as the tool can be found within the field of view of the SC3D system camera. The positioning requirements for the transfer cart can be relaxed as long as the gantry robot within the glovebox has four axes of motion.

The system performs automatic calibration, which allows the imaging software to compensate for distortion inherent in the optics. The auto-calibration makes the association between the camera pixel space and robot space, so the target location can be translated to coordinates for the motion system. This calibration needs to be performed anytime the camera system is modified or removed for repair.



A rigid camera mount was designed that allows easy camera replacement, but self-centers and secures the camera in place. The mount bolts to the quick change tool plate of the robot, as do the lighting fixtures, as shown in the figure of the vision guidance system prototype.

High-intensity LED lighting provides diffused 365-nm (red) illumination of the calibration grid as well as the targets to be located. A 365-nm center frequency bandpass filter is used on the camera to essentially eliminate the effects of ambient light on the imaging of the targets. The bandpass filter was very effective in eliminating the effects of mercury vapor overhead lighting and fluorescent tube lighting.

The INL-developed integration software marries the SC3D imaging software with gantry robot motion control software. Each is modular, based on Microsoft Windows' XP operating system, and transportable from one system to another. This becomes important in the research and development world, as programs develop and new equipment becomes available for an application.

We chose a charge-injection-device (CID) camera because of the high radiation areas in which the vision guidance system will operate. We are also considering CMOS cameras as options for the imaging device. Although not radiation hardened, CMOS cameras appear to be more tolerant of radiation fields than are CCD cameras. The current camera interface is specified as an NTSC video output to a framegrabber card. As the technology develops, other interfaces, such as Ethernet or CameraLink, might be considered to transfer images to the vision guidance software. This improvement would take advantage of higher-resolution camera interfaces but would involve significant modification to existing vision guidance software.

A second SC3D system without a radiation-hardened camera could be implemented within the maintenance glovebox system for locating and picking equipment and tools from the transfer cart and transporting them to maintenance locations within the glovebox. This capability in the glovebox relaxes the positioning requirements that would otherwise be imposed on the transfer cart and the need for multiple fixtures to hold rigid the tools and equipment being transferred from the closure cell.

CONCLUSION

A single-camera 3-D-imaging vision guidance system will provide the means for a four-axes gantry robot to pick and place equipment and tools from unfixtured and loosely fixtured locations within the waste package closure cell. The software will be transportable from one platform to another as applications change and equipment is upgraded. The SC3D system offers a simple yet effective means of implementing a vision guidance system in a remote hot cell.